

DIJET AZIMUTHAL ANISOTROPY IN HIGH ENERGY DIS

Vladimir Skokov (RBRC BNL)

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A. Dumitru, T. Lappi and V. S.

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INTRODUCTION I

EIC goals:

- Explore the distribution of sea quarks and gluons and their spins in space and momentum inside nucleon
- Saturation density and its effect of distribution of quarks and gluons.
Universality at high energy?
- Effect of nuclear environment on distribution of quarks and gluons

Saturation idea (Gribov, Levin, Ryskin 1983)

- Experiments supported by theory (BFKL evolution equation) established that gluon distribution grows rapidly as x gets smaller
(x is longitudinal momentum fraction)
- Gluon density cannot grow arbitrary large \leadsto violation of unitarity limit for forward scattering amplitude
- Saturation: at high transverse gluon density (Q_s^2) gluon merge \leadsto taming further growth. In theory this corresponds to nonlinear regime of QCD evolution dynamics (BK equation)
- Natural way to enhance saturation effects is to probe heavy nuclear target at high energy. $Q_s^2 \propto A^{1/3} \sqrt{s}^{0.3}$. Theoretical approaches limited to $Q_s \gg \Lambda_{\text{QCD}}$

INTRODUCTION II

Experimental hints of saturation

- Cronin enhancement at large transverse momenta is replaced by suppression at all values of momenta at forward rapidity in d-Au at RHIC. Theory: at forward rapidity nucleus is probed at highly saturated state.

Kharzeev, Kovchegov, Tuchin Phys.Lett. B599 (2004) 23-31;

Albacete et.al. Phys.Rev.Lett. 92 (2004) 082001

- Suppression of dihadron correlation at forward rapidities in d-Au. Theory: gluons carry transverse momentum of order $Q_s \sim$ increase of momentum imbalance. Effect is strongest at forward rapidities, where nuclear saturation momentum is largest.

Albacete, Marquet Phys.Rev.Lett. 105 (2010) 162301

EIC provides unique opportunity to study dihadron correlation

- Negligible probability for multiple emission. No 'pedestal' effect due to uncorrelated scattering
- Model-independent information on Q and x

INTRODUCTION III

There are two different unintegrated gluon distributions (UGD):

- **Dipole** gluon distribution ($G^{(2)}$) + linear polarized partner ($h^{(2)}$).
Appears in many processes. Small x evolution is well understood (BFKL/BF evolution equations)
- **Weizsäcker-Williams** gluon distribution ($G^{(1)}$) + linear polarized partner ($h^{(1)}$).

WW UGD appears exclusively only in dijet DIS \leadsto unique probe of **WW** UGD in saturation regime

As in p-A or d-A, saturation in e-A \leadsto decrease of back-to-back dihadron correlation

L. Zheng, E. C. Aschenauer, J. H. Lee and B. W. Xiao

Phys. Rev. D **89**, 7, 074037 (2014)

In this talk: structure of back-to-back peak

WEIZSÄCKER-WILLIAMS GLUON DISTRIBUTION: LINEARLY POLARIZED GLUONS IN UNPOLARIZED TARGET

P. Mulders and J. Ridrigues Phys.Rev. D63 (2001) 094021

D. Boer, P. Mulders, C. Pisano Phys.Rev. D80 (2009) 094017

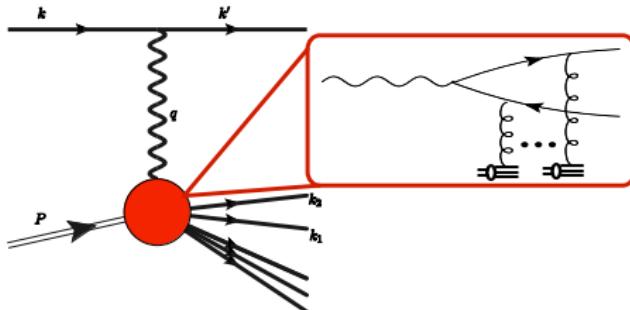
A. Metz and J. Zhou Phys.Rev. D84 (2011) 051503

F. Dominguez, C. Marquet, B.-W. Xiao, F. Yuan Phys.Rev. D83 (2011) 105005

F. Dominguez, J.-W. Qiu, B.-W. Xiao, F. Yuan Phys.Rev. D85 (2012) 045003

- WW Linearly polarized gluons (partner of conventional WW) are present even in unpolarized hadrons; it contributes with $\cos(2\phi)$ azimuthal angular dependence
- Origin: averaged quantum interference of different helicity states between scattering amplitude and its complex conjugate
- It is present only at non-zero transverse momentum: transverse momentum-dependent distribution
- Small x behaviour of polarization WW Linearly polarized gluon distribution is largely unknown

DIJET PRODUCTION IN DIS



- DIS dijet production: $\gamma^* A \rightarrow q \bar{q} X$
- Multiple scatterings of (anti) quark are accounted for by resummation:

$$U(\mathbf{x}) = \mathbb{P} \exp \left\{ ig \int dx^- A^+(x^-, \mathbf{x}_\perp) \right\}$$

- In color dipole model this process corresponds to

$$\frac{d\sigma^{\gamma^* A \rightarrow q \bar{q} X}}{d^3 k_1 d^3 k_2} = N_c \alpha_{em} e_q^2 \delta(p^+ - k_1^+ - k_2^+) \int \frac{d^2 x_1}{(2\pi)^2} \frac{d^2 x_2}{(2\pi)^2} \frac{d^2 y_1}{(2\pi)^2} \frac{d^2 y_2}{(2\pi)^2} \exp(-i\mathbf{k}_1(\mathbf{x}_1 - \mathbf{y}_1) - i\mathbf{k}_2(\mathbf{x}_2 - \mathbf{y}_2))$$

$$\sum_{\alpha\beta} \psi_{\alpha\beta}^{T,L\gamma}(\mathbf{x}_1 - \mathbf{x}_2) \psi_{\alpha\beta}^{T,L\gamma*}(\mathbf{y}_1 - \mathbf{y}_2) \left[1 + \frac{1}{N_c} \left(\langle \text{Tr } U(\mathbf{x}_1) U^\dagger(\mathbf{y}_1) U(\mathbf{y}_2) U^\dagger(\mathbf{x}_2) \rangle \right. \right.$$

$$\left. \left. - \langle \text{Tr } U(\mathbf{x}_1) U^\dagger(\mathbf{x}_2) \rangle - \langle \text{Tr } U(\mathbf{y}_1) U^\dagger(\mathbf{y}_2) \rangle \right) \right] \quad \uparrow \text{Quadrupole contribution}$$

- Splitting wave function of γ^* with longitudinal momentum p^+ and virtuality Q^2
- This expression can be computed without any further simplifications with **quadrupole**, but no direct relation to TMD functions

DIJET PRODUCTION IN DIS

- In correlation limit (almost back-to-back jets) $\mathbf{P} = (\mathbf{k}_1 - \mathbf{k}_2)/2$ is much larger than $\mathbf{q} = \mathbf{k}_1 + \mathbf{k}_2$, for conjugate variables, $u \ll v$, where $\mathbf{u} = \mathbf{x}_1 - \mathbf{x}_2$ and $\mathbf{v} = (\mathbf{x}_1 + \mathbf{x}_2)/2$. Expand in u .
- Expansion of quadrupole brings gradients of Wilson lines.
- Allows to reduce to 2 point functions

$$xG_{WW}^{ij}(\mathbf{k}) = \frac{8\pi}{S_\perp} \int \frac{d^2x}{(2\pi)^2} \frac{d^2y}{(2\pi)^2} e^{-\mathbf{k} \cdot (\mathbf{x}-\mathbf{y})} \langle A_a^i(\mathbf{x}) A_a^j(\mathbf{y}) \rangle, \quad A^i(\mathbf{x}) = \frac{1}{ig} U^\dagger(\mathbf{x}) \partial_i U(\mathbf{x})$$

WW Color Electric field ↑

- Decomposition to **conventional** and **traceless** contribution

$$xG_{WW}^{ij} = \frac{1}{2} \delta^{ij} x \textcolor{blue}{G^{(1)}} - \frac{1}{2} \left(\delta^{ij} - 2 \frac{q^i q^j}{q^2} \right) x \textcolor{red}{h_\perp^{(1)}}$$

WEIZSÄCKER-WILLIAMS GLUON DISTRIBUTION

- Contribution to azimuthal anisotropy of dijet production

$$E_1 E_2 \frac{d\sigma^{\gamma_L^* A \rightarrow q\bar{q}X}}{d^3 k_1 d^3 k_2 d^2 b} = \alpha_{em} e_q^2 \alpha_s \delta(x_{\gamma^*} - 1) z^2 (1-z)^2 \frac{8\epsilon_f^2 P_\perp^2}{(P_\perp^2 + \epsilon_f^2)^4}$$
$$\times \left[x \textcolor{blue}{G^{(1)}}(x, q_\perp) + \underline{\cos(2\phi)} \ x \textcolor{red}{h_\perp^{(1)}}(x, q_\perp) \right].$$

$$E_1 E_2 \frac{d\sigma^{\gamma_T^* A \rightarrow q\bar{q}X}}{d^3 k_1 d^3 k_2 d^2 b} = \alpha_{em} e_q^2 \alpha_s \delta(x_{\gamma^*} - 1) z(1-z)(z^2 + (1-z)^2) \frac{\epsilon_f^4 + P_\perp^4}{(P_\perp^2 + \epsilon_f^2)^4}$$
$$\times \left[x \textcolor{blue}{G^{(1)}}(x, q_\perp) - \frac{2\epsilon_f^2 P_\perp^2}{P_\perp^4 + \epsilon_f^4} \underline{\cos(2\phi)} \ x \textcolor{red}{h_\perp^{(1)}}(x, q_\perp) \right].$$

z is long. momentum fraction of photon carried by quark

$$\epsilon_f^2 = z(1-z)Q^2$$

SEVERAL USEFUL LIMITS

- Scattering of real photon $Q = 0$

$$E_1 E_2 \frac{d\sigma^{\gamma_L^* A \rightarrow q\bar{q}X}}{d^3 k_1 d^3 k_2 d^2 b} = 0$$

$$E_1 E_2 \frac{d\sigma^{\gamma_T^* A \rightarrow q\bar{q}X}}{d^3 k_1 d^3 k_2 d^2 b} = \alpha_{em} e_q^2 \alpha_s \delta(x_{\gamma^*} - 1) z(1-z)(z^2 + (1-z)^2) \frac{1}{P_\perp^4} \ x \textcolor{blue}{G}^{(1)}(x, q_\perp)$$

- Real photon does not give $\cos(2\phi)$ transverse spin correlation that can match with spin correlation generated by $\textcolor{red}{h}_\perp^{(1)}(x, q_\perp)$

SEVERAL USEFUL LIMITS

- $Q \gg P_\perp$

$$E_1 E_2 \frac{d\sigma^{\gamma_L^{*A} \rightarrow q\bar{q}X}}{d^3 k_1 d^3 k_2 d^2 b} = \alpha_{em} e_q^2 \alpha_s \delta(x_{\gamma^*} - 1) z^2 (1-z)^2 \frac{8P_\perp^2}{\epsilon_f^6} \\ \times \left[x \textcolor{blue}{G}^{(1)}(x, q_\perp) + \underline{\cos(2\phi)} \ x \textcolor{red}{h}_\perp^{(1)}(x, q_\perp) \right].$$

$$E_1 E_2 \frac{d\sigma^{\gamma_T^{*A} \rightarrow q\bar{q}X}}{d^3 k_1 d^3 k_2 d^2 b} = \alpha_{em} e_q^2 \alpha_s \delta(x_{\gamma^*} - 1) z (1-z) (z^2 + (1-z)^2) \frac{1}{\epsilon_f^4} \\ \times \left[x \textcolor{blue}{G}^{(1)}(x, q_\perp) - \frac{2P_\perp^2}{\epsilon_f^2} \underline{\cos(2\phi)} \ x \textcolor{red}{h}_\perp^{(1)}(x, q_\perp) \right].$$

- Relative anisotropy is larger for longitudinal photon
- For arbitrary Q : non-trivial dependence of anisotropy

PHYSICAL INTERPRETATION

- Conventional WW: probability distribution

$$\delta_{ij} = \varepsilon_+^{*i} \varepsilon_+^j + \varepsilon_-^{*i} \varepsilon_-^j$$

- Gluon helicity: difference of probability distributions

$$i\epsilon_{ij} = \varepsilon_+^{*i} \varepsilon_+^j - \varepsilon_-^{*i} \varepsilon_-^j$$

- $h^{(1)}$: transverse spin correlation function of gluons in two orthogonal polarization states

$$2 \frac{q^i q^j}{q^2} - \delta^{ij} = i(\varepsilon_+^{*i} \varepsilon_-^j - \varepsilon_-^{*i} \varepsilon_+^j)$$

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F. Dominguez, C. Marquet, B.-W. Xiao, F. Yuan Phys.Rev. D83 (2011) 105005
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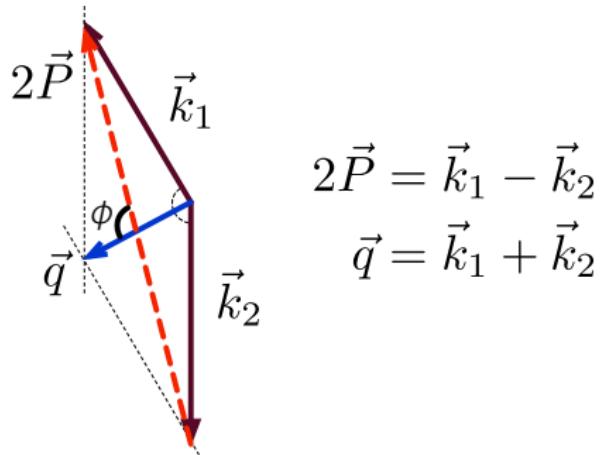
CORRELATIONS LIMIT RESULTS FOR $\gamma_{\parallel,\perp}^*$

$$E_1 E_2 \frac{d\sigma^{\gamma_L^* A \rightarrow q\bar{q}X}}{d^3 k_1 d^3 k_2 d^2 b} = \alpha_{em} e_q^2 \alpha_s \delta(x_{\gamma^*} - 1) z^2 (1-z)^2 \frac{8\epsilon_f^2 P_\perp^2}{(P_\perp^2 + \epsilon_f^2)^4} \times [x \mathbf{G}^{(1)}(x, q_\perp) + \frac{\cos(2\phi)}{x} x \mathbf{h}_\perp^{(1)}(x, q_\perp)]$$

$$E_1 E_2 \frac{d\sigma^{\gamma_T^* A \rightarrow q\bar{q}X}}{d^3 k_1 d^3 k_2 d^2 b} = \alpha_{em} e_q^2 \alpha_s \delta(x_{\gamma^*} - 1) z (1-z) (z^2 + (1-z)^2) \frac{\epsilon_f^4 + P_\perp^4}{(P_\perp^2 + \epsilon_f^2)^4}$$

$$\times \left[x \mathbf{G}^{(1)}(x, q_\perp) - \frac{2\epsilon_f^2 P_\perp^2}{\epsilon_f^4 + P_\perp^4} \frac{\cos(2\phi)}{x} x \mathbf{h}_\perp^{(1)}(x, q_\perp) \right]$$

- Jets are almost back-to-back. Note: this is not about suppression of back-to-back peak, but rather about the structure of back to back correlation.
- Azimuthal anisotropy is in angle between P and q , denoted by ϕ .**
- Is $h_\perp^{(1)}$ important at small x ?



NUMERICS

- McLerran-Venugopalan initial conditions at $Y = \ln x_0/x = 0$

$$S_{\text{eff}}[\rho^a] = \int dx^- d^2x_\perp \frac{\rho^a(x^-, x_\perp) \rho^a(x^-, x_\perp)}{2\mu^2}$$

for

$$U(x_\perp) = \mathbb{P} \exp \left\{ ig^2 \int dx^- \frac{1}{\nabla_\perp^2} t^a \rho^a(x^-, x_\perp) \right\}$$

- Quantum evolution at $Y > 0$ is accounted for by solving JIMWLK-B using Langevin method

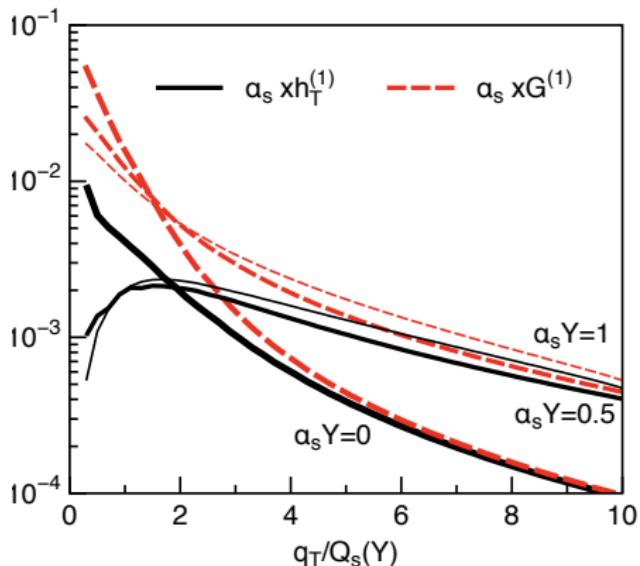
$$\partial_Y U(z) = U(z) \frac{i}{\pi} \int d^2u \frac{(z-u)^i \eta^j(u)}{(z-u)^2} - \frac{i}{\pi} \int d^2v U(v) \frac{(z-v)^i \eta^j(v)}{(z-v)^2} U^\dagger(v) U(z).$$

The Gaussian white noise $\eta^i = \eta_a^i t^a$ satisfies $\langle \eta_i^a(z) \rangle = 0$ and

$$\langle \eta_i^a(z) \eta_j^b(y) \rangle = \alpha_s \delta^{ab} \delta_{ij} \delta^{(2)}(z-y).$$

L. D. McLerran and R. Venugopalan, Phys. Rev. D49, 2233 (1994)
J.-P. Blaizot, E. Iancu and H. Weigert, Nucl. Phys. A713, 441 (2003)
T. Lappi and H. Mäntysaari, Eur. Phys. J. C73, 2307 (2013)

SMALL x EVOLUTION



McLerran-Venugopalan model (classical sources of WW field) results

$$xh_{\perp}^{(1)} = \frac{S_{\perp}}{2\pi^3 \alpha_s} \frac{N_c^2 - 1}{N_c} \int_0^{\infty} dr r \frac{J_2(q_{\perp} r)}{r^2 \ln \frac{1}{r^2 \Lambda^2}} \left(1 - \exp \left(-\frac{1}{4} r^2 Q_s^2 \right) \right)$$

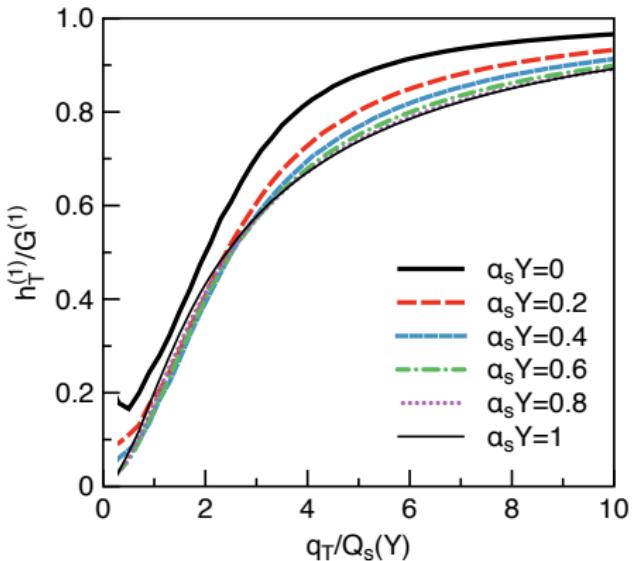
$$xG^{(1)} = \frac{S_{\perp}}{2\pi^3 \alpha_s} \frac{N_c^2 - 1}{N_c} \int_0^{\infty} dr r \frac{J_2(q_{\perp} r)}{r^2} \left(1 - \exp \left(-\frac{1}{4} r^2 Q_s^2 \right) \right)$$

Large $q_{\perp} \gg Q_s$: $xh_{\perp}^{(1)} = xG^{(1)} \propto 1/q_{\perp}^2$

Small $q_{\perp} \ll Q_s$: $xh_{\perp}^{(1)} \propto q_{\perp}^0$ $xG^{(1)} \propto \ln \frac{Q_s^2}{q_{\perp}^2}$

- at large q_{\perp} , saturation of positivity bound $h_{\perp}^{(1)} \rightarrow G^{(1)}$, as also was found in pert. twist 2 calculations of small x field of fast quark
- at small q_{\perp} , $h_{\perp}^{(1)}/G^{(1)} \rightarrow 0$
- both functions decrease fast as functions of q_{\perp} : best measured when $q_{\perp} \approx Q_s$. Nuclear target!

SMALL x EVOLUTION II



- Fast departure from MV ($\alpha_s Y = 0$)
- Slow evolution towards smaller x
- $h_\perp^{(1)}$ is large at small x
- Note: q_\perp is scaled by exponentially growing $Q_s(Y)$: ratio at fixed q_\perp decreases with rapidity.
Emission of small x gluons reduces degree of polarization.
- Approximate geometric scaling at small x .

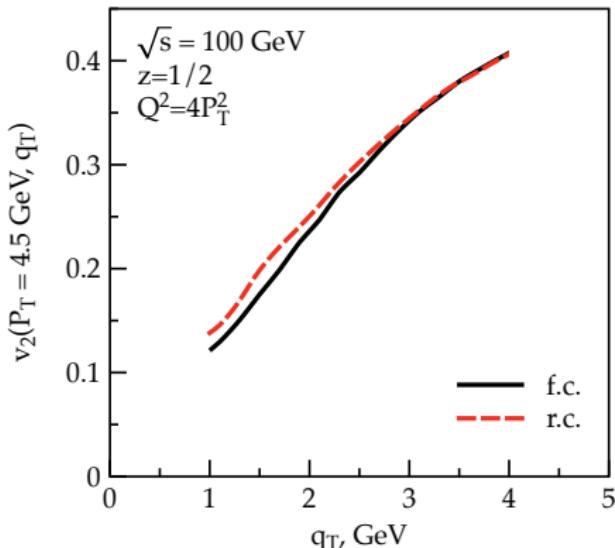
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SECOND HARMONICS OF AZIMUTHAL ANISOTROPY: q_\perp -DEPENDENCE

- By analogy to HIC

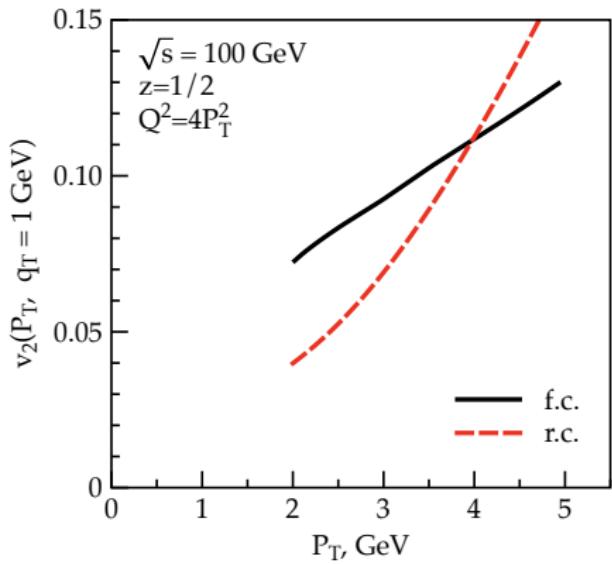
$$v_2(P_\perp, q_\perp) = \langle \cos 2\phi \rangle$$

- Fixed coupling results (“f.c.”) are for $\alpha_s = 0.15$
- At this fixed P_\perp not very significant dependence on prescription for α_s
- Increase of v_2 is due to increasing $h_\perp^{(1)}(q_\perp)/G^{(1)}(q_\perp)$



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SECOND HARMONICS OF AZIMUTHAL ANISOTROPY: P_\perp -DEPENDENCE



- Fixed coupling results significantly different from running coupling
- Large azimuthal anisotropy in both cases
- Increasing P_\perp increases x and suppresses evolution effects driving v_2 towards its MV value

$$x = \frac{1}{s} \left(q_\perp^2 + \frac{1}{z(1-z)} P_\perp^2 \right)$$

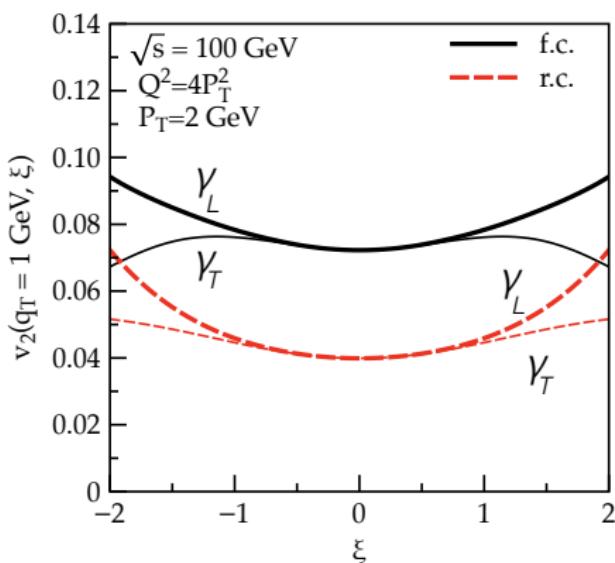
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DEPENDENCE ON LONGITUDINAL MOMENTUM

- To probe longitudinal structure

$$\xi = \ln \frac{1-z}{z}$$

- Long-range “rapidity” correlation
- Mild increase for large ξ because asymmetric dijets probe target at larger values of x



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MONTE CARLO EVENT GENERATOR

- DIS event with random Q^2 , W^2 , photon polarization, as well as P_\perp and q_\perp
- Input: \sqrt{s} and A
- Q_s and target area are adjusted according to A
- Output: Parton 4-momentum etc
- Pythia afterburner \rightarrow particles
- This does not account for background

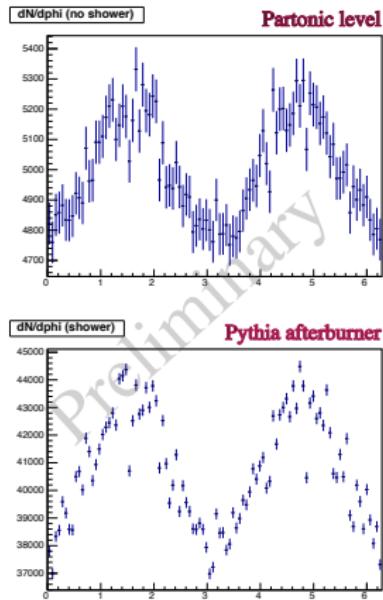


Fig. by T. Ulrich

Shower: for each pion pair from opposite hemispheres, \mathbf{P}_\perp and \mathbf{q}_\perp are constructed

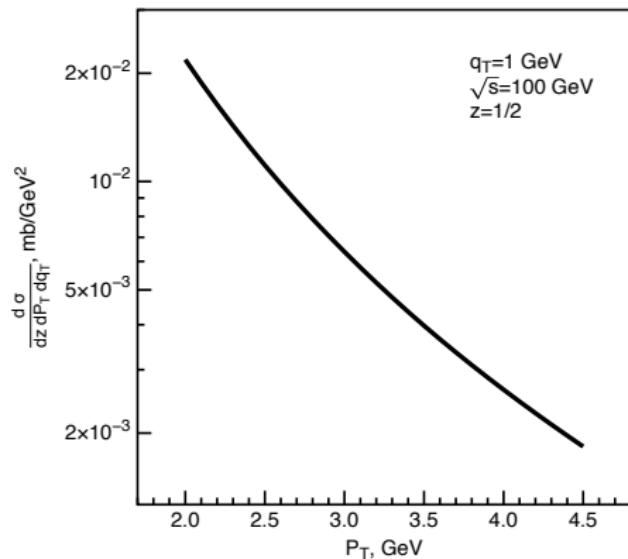
A. Dumitru, V. S. and T. Ulrich work in progress

CONCLUSIONS

- In correlations limit, DIS dijets to probe WW gluon distribution
- Gluon distribution has two distinct contributions: isotropic WW $xG^{(1)}$ and linearly polarized, $\cos(2\phi)$ anisotropic, $xh^{(1)}$ – interference of gluons in orthogonal polarizations
- Classical McLerran-Venugopalan model gives large relative anisotropy at large momentum, both $G^{(1)}$ and $h_{\perp}^{(1)}$ are proportional to $1/q_{\perp}^2$
- JIMWLK-B: $h^{(1)}$ grows as fast as $G^{(1)}$
- Not significant dependence on prescription for α_s
- Long-range in “rapidity”
- Survives in MC events summed over polarization and different distributions of q , z , P_{\perp} , q_{\perp} etc.
- Survives after Pythia shower, even without performing jet reconstruction

CROSS-SECTION FOR SIGNAL

- Cross-section summed with respect to γ^* polarizations and integrated over angles
- \sqrt{s} is given for γ^*A CM



A. Dumitru, and V. S., 2015